Vol. 7 No. 1 (2026), Pages 56-65

GEOGRAPHIA
Jurnal Pendidikan dan Penelitian Geografi

ISSN: 2774-6968

HYDROGEOCHEMICAL CHARACTERISTICS ANALYSIS OF GROUNDWATER ALONG COASTAL AREA OF UJONG PANCU, ACEH BESAR REGENCY

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Journal Website: http://ejurnal.unima.ac.id/index.php/geographia

DOI: https://doi.org/10.53682/s1pmq723
(Accepted: 12-03-2026; Revised: 25-04-2026; Approved: 05-06-2026)

ABSTRACT
Groundwater is the primary source of fresh water for communities in the coastal area of Ujong Pancu, Peukan Bada, Aceh Besar. However, limited assessments of its suitability for domestic use, combined with geological conditions dominated by high-porosity alluvial deposits (Qh), increase its vulnerability to contamination. Therefore, this study aims to analyze the hydrogeochemical characteristics and evolution of groundwater and to identify the controlling geochemical processes. A total of 10 groundwater samples were collected from dug wells and analyzed for major cations (Na, K, Ca, and Mg) and anions (Cl, SO_4, and HCO_3). The results were interpreted using Stiff and Piper diagrams to determine hydrochemical facies and groundwater evolution. The results show that groundwater is dominated by Ca–Mg–HCO_3, mixed facies, and Na–HCO_3–SO_4. The evolution of groundwater chemistry indicates carbonate mineral dissolution and cation exchange processes, in which Ca–Mg is progressively replaced by Na along the groundwater flow path. Several samples exhibit balanced Ca and HCO_3 concentrations, indicating meteoric water characteristics. In conclusion, groundwater hydrogeochemistry in the Ujong Pancu coastal area is primarily controlled by water–rock interaction and internal aquifer processes.

Keywords: *Coastal area, Groundwater characteristics, Hydrogeochemistry, Piper diagram, Stiff diagram.*

INTRODUCTION

Groundwater resources constitute one of the primary sources of fresh water for communities in the coastal area of Ujong Pancu, Peukan Bada, Aceh Besar. The high dependence of local communities on groundwater for domestic purposes makes its quality and sustainability critically important. (Goal et al., 2023). However, coastal areas are generally highly vulnerable to contamination, particularly due to seawater intrusion, which can significantly degrade groundwater quality (Han & Currell, 2022).

Previous studies have shown that groundwater hydrogeochemical characteristics in coastal areas are strongly influenced by water–rock interactions, geological conditions, and aquifer system dynamics (Haikal et al., 2024). Previous studies have shown that groundwater hydrogeochemical characteristics in coastal areas are strongly influenced by water–rock interactions, geological conditions, and aquifer system dynamics. Nevertheless, hydrogeochemical studies that specifically examine groundwater chemical types and hydrogeochemical evolution in the Ujong Pancu coastal area remain limited (You et al., 2024). Most existing research has focused on regional geology or general groundwater quality assessments, without detailed analysis of the geochemical processes controlling groundwater composition, including early indications of seawater intrusion (Goyal et al., 2023). In addition, there is a lack of studies integrating the use of Stiff and Piper diagrams to simultaneously identify hydrochemical facies and evaluate hydrogeochemical evolution in this region (Irham et al., 2021). Such an integrated approach is essential to provide a more comprehensive understanding of the governing geochemical processes and the potential influence of seawater intrusion on groundwater systems.

Based on these considerations, the main research questions of this study are formulated as follows: (1) what the hydrogeochemical characteristics of groundwater in the Ujong Pancu coastal area are, (2) what the dominant groundwater chemical types are, and (3) how does hydrogeochemical evolution occur, including indications of groundwater quality.

In terms of major ion composition, groundwater is primarily dominated by cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}), as well as the anion bicarbonate (HCO_3^{-}). The elevated concentration of bicarbonate reflects the dissolution of carbonate minerals, which represents a key geochemical process in the study area. Furthermore, the relative enrichment of sodium compared to calcium and magnesium suggests the occurrence of cation exchange processes, whereby Ca^{2+} and Mg^{2+} in the groundwater are replaced by Na^{+} derived from aquifer materials (Yusuf et al., 2021). hydrogeochemical evolution in the Ujong Pancu coastal area is characterized by a transition from carbonate-controlled freshwater to sodium-enriched water driven by ion exchange processes. Although the groundwater quality is generally good, continuous monitoring is necessary to ensure its long-term sustainability under increasing environmental and anthropogenic pressures (Mohamed et al., 2022).

This study aims to analyze groundwater hydrogeochemical characteristics by determining chemical types and interpreting hydrogeochemical evolution using Stiff and Piper diagrams (Nayak et al., 2022). The novelty of this research lies in its integrative approach, combining hydrochemical facies analysis with systematic interpretation of geochemical processes to provide a more comprehensive understanding of groundwater conditions in the Ujong Pancu coastal area.

Regionally, the Ujong Pancu coastal area is dominated by Alluvium deposits (Qh) and the Peunasu Formation (Tlp) (Bennet et al., 1981), composed of sandstone, conglomerate, shale, mudstone, and reef limestone with relatively high porosity (Sartika et al., 2020). These geological conditions increase aquifer vulnerability to contamination, including the potential for seawater intrusion (Muhni et al., 2022). The dominance of unconsolidated coastal alluvial deposits such as sand, silt, and gravel further enhances the likelihood of seawater migration into the groundwater system (Wei et al., 2022).

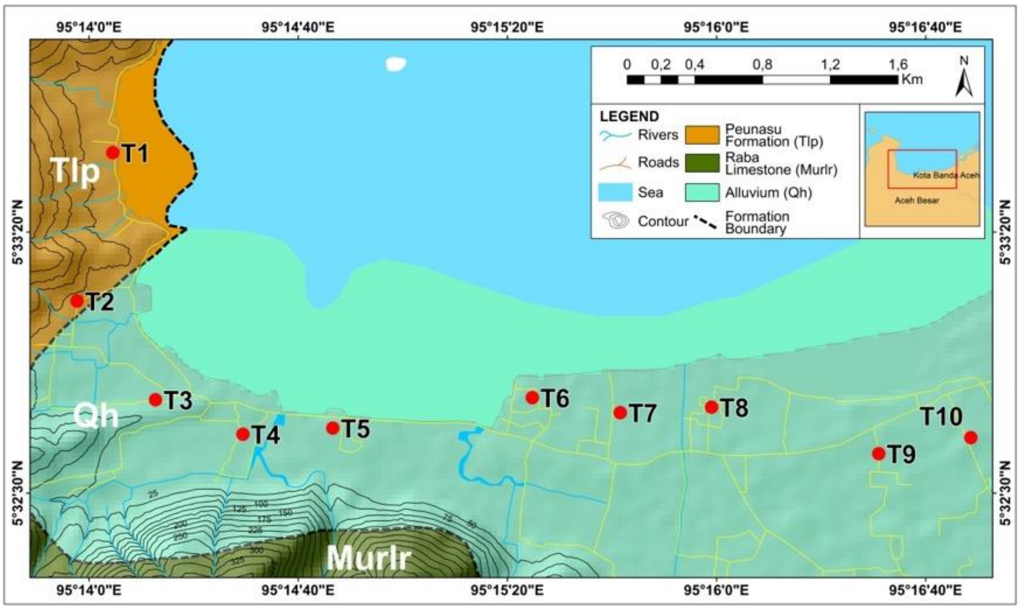

Figure 1. Map of The Research Location and Setting Geology

RESEARCH METHODS

This study was conducted through several stages. The initial stage involved a literature review to understand the regional geological setting, particularly lithologies that may influence groundwater characteristics (Subba Rao et al., 2024), followed by a preliminary survey to identify the distribution of dug wells along the coastal area of Ujong Pancu, Peukan Bada, Aceh Besar. The next stage comprised direct field observations of dug wells and groundwater sampling from wells that exhibited distinct physical characteristics compared with others, such as odor, taste, or turbidity (Ullah et al., 2022). A total of 10 groundwater samples were collected in light-resistant bottles and stored at room temperature prior to laboratory analysis.

Groundwater samples were analyzed to determine the concentrations of major cations and anions using standard laboratory procedures. The analysis of major cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) was carried out using Atomic Absorption Spectrophotometry (AAS) (Habib et al., 2024). This method was selected due to its high accuracy and sensitivity in detecting dissolved ions in groundwater. Bicarbonate (HCO_3^-) concentrations were determined using the titration method with standard hydrochloric acid (HCl) based on alkalinity measurements (Le et al., 2022). Chloride (Cl^-) was analyzed using the titration method, while sulfate (SO_4^{2-}) was measured using a spectrophotometric method. All instruments were calibrated using standard solutions prior to analysis to ensure accuracy. The quality of laboratory analytical results can be evaluated using the Charge Balance Error (CBE) method proposed by R.A. Freeze et al. (1979), which is calculated using the following equation:

$$BE = \frac{\sum Zmc - \sum Zma}{\sum Zmc + \sum Zma} \ x \ 100$$

Where Z represents the ionic valence, mc is the molality of cations, and ma is the molality of anions. The CBE value is considered acceptable when it is less than 5% (Yu et al., 2022). This evaluation is essential to ensure the reliability of hydrochemical data used in hydrogeochemical analysis. Furthermore, a proper understanding and management of potential contamination sources are crucial for protecting and maintaining groundwater quality (Maria et al., 2021).

Laboratory testing was performed to determine major element concentrations, including major cations (Na, K, Ca, Mg) and major anions (Cl, SO_4, HCO_3) (Mairizki et al., 2021). The analytical results were subsequently interpreted to characterize groundwater hydrogeochemistry using Stiff and Piper diagrams (Haikal et al., 2024). The Piper diagram was applied to identify hydrochemical facies and groundwater evolution (Chai et al., 2020), whereas the Stiff diagram was used to visually compare ionic composition patterns and to evaluate lithological influence and potential geochemical processes (Irham et al., 2021).

Figure 2. Water Sampling Process in the Research Area

RESULTS AND DISCUSSION

The results of laboratory analysis of groundwater major elements were expressed in meq/L after conversion from mg/L. The cation data (Na, K, Ca, and Mg) and the anion data (Cl, SO_4, and HCO_3) are presented in Table 1. Based on the ionic composition of groundwater samples from Ujong Pancu, the dominant cations are Sodium (Na) and Calcium (Ca). This composition indicates the occurrence of relatively intensive ion exchange processes, in which groundwater initially dominated by Ca–Mg in the recharge zone evolves toward Na dominance along the groundwater flow path away from the recharge source.

Table 1. Hydrogeochemical Test Results on Groundwater

N	X	Y	Kation (meq/L)				Anion (meq/L)		
			Na	K	Ca	Mg	Cl	SO_4	HCO_3
T1	95,2346028	5,5597806	5,37	0,23	4,16	0,24	0,001	1,60	0,05
T2	95,2326972	5,5518889	4,42	0,03	5,20	0,16	0,002	1,54	6,00
T3	95,2368694	5,5466361	2,56	0,55	1,28	0,64	0,001	0,67	0,80
T4	95,2415111	5,5448028	3,57	0,03	6,08	0,16	0,002	2,00	6,00
T5	95,2462861	5,5451278	0,84	0,21	3,60	0,16	0,001	0,35	5,60
T6	95,2568861	5,5467472	4,74	0,02	1,28	1,52	0,001	1,75	11,60
T7	95,2615583	5,5459500	4,76	1,92	2,72	0,16	0,004	8,44	0,40
T8	95,2664083	5,5462417	2,32	0,12	3,12	0,72	0,001	0,69	4,80
T9	95,2752944	5,5437694	1,80	1,00	2,08	1,52	0,001	0,75	4,40
T10	95,2801833	5,5446222	3,80	0,07	2,80	0,48	0,002	0,75	5,99

Among the anions, Bicarbonate (HCO_3^-) and Sulfate (SO_4^{2-}) are dominant. This condition reflects groundwater that has evolved from the recharge zone and is influenced by carbonate mineral dissolution, as indicated by a significant increase in bicarbonate concentration. The carbonate ions are inferred to originate from the dissolution of carbonate lithologies composing the aquifer, such as reef limestone within the Peunasu Formation (Tlp) and coastal sand deposits (Qh) (Bennet et al., 1981). Meanwhile, the low Chloride (Cl^-) concentrations in all samples suggest that the influence of seawater intrusion has not developed significantly in the groundwater of the study area.

The ion concentrations of both cations and anions were subsequently interpreted using the Stiff diagram (Figure 5) and the Piper diagram to analyze groundwater hydrogeochemical evolution and to classify the dominant groundwater types and characteristics more comprehensively, as follows:

Stiff diagram analysis

Based on the concentrations of major cations (Na, K, Ca, and Mg) and anions (Cl, SO_4, and HCO_3) expressed in meq/L from 10 groundwater samples, several hydrogeochemical interpretations can be made to identify the dominant geochemical processes controlling groundwater composition (C. Wu et al., 2021). In general, the dominant cations are Ca and Na, while K and Mg occur in relatively lower concentrations in most samples. The relatively high Ca concentrations observed in samples T2, T4, T6, T7, and T10 indicate the influence of carbonate mineral dissolution from aquifer-forming rocks. Meanwhile, increasing Na concentrations in several samples, such as T1, T5, T6, and T10, suggest the occurrence of cation exchange processes as groundwater flows away from the recharge zone. The dominance of Ca in several samples reflects relatively young groundwater derived from recharge areas (recharge water), whereas the increase in Na indicates progressive chemical evolution of groundwater along the flow path (H. Wu et al., 2019).

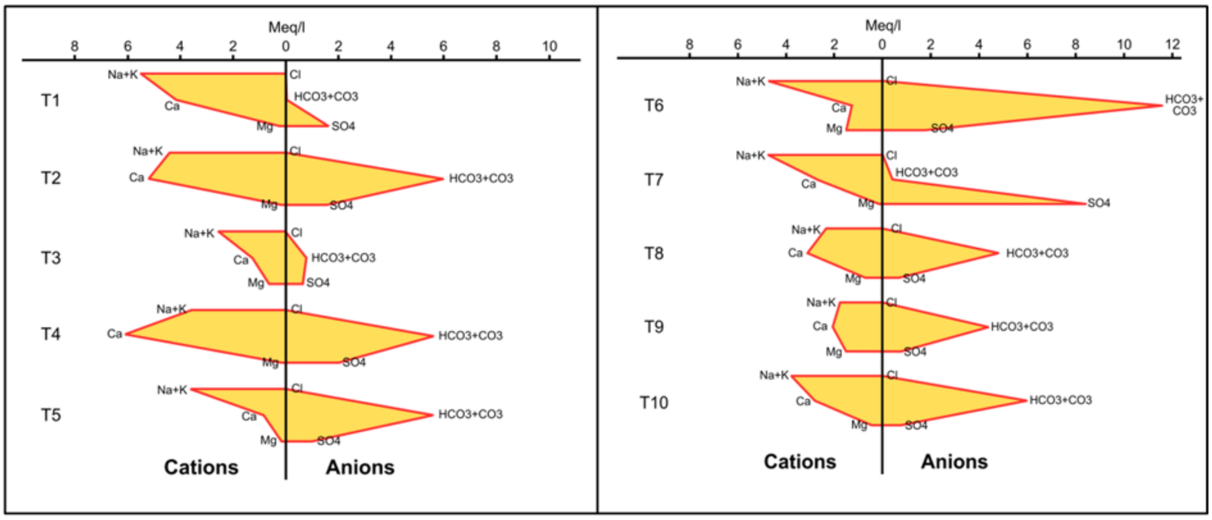

Figure 3. Stiff Diagram of the Research Area

Among the anions, HCO_3 is the dominant ion in most samples, particularly in T6 (11.60 meq/L), T2 (6.00 meq/L), T4 (6.00 meq/L), T5 (5.60 meq/L), and T10 (5.99 meq/L). The high concentration of HCO_3 indicates that carbonate mineral dissolution is the primary geochemical process controlling groundwater chemistry. In sample T7, SO_4 shows a relatively higher concentration (8.44 meq/L) compared to other samples, which may indicate the dissolution of sulfate-bearing minerals or the influence of local geochemical conditions within the aquifer system. Meanwhile, the concentration of Cl in all samples is relatively low (approximately 0.001–0.004 meq/L), indicating that seawater intrusion has not significantly influenced the groundwater system, despite the study area being located in a coastal environment.

Based on the observed ionic composition patterns, the hydrogeochemical evolution of groundwater can be interpreted in several stages. The first stage represents the recharge zone, characterized by the dominance of the Ca–HCO_3 facies with relatively balanced ionic composition, as observed in samples T8 and T9. The next stage represents a carbonate dissolution zone, marked by increasing concentrations of Ca and HCO_3 due to interaction between groundwater and carbonate lithologies forming the aquifer (Mohamed et al., 2022), as shown in samples T2, T4, and T6. Finally, in areas farther from the recharge zone, groundwater evolves through cation exchange processes, where Ca is gradually replaced by Na, resulting in a tendency toward Na–HCO_3 facies, as observed in samples T1, T5, and T10.

Piper diagram analysis

Based on the plotting results on the Piper diagram, groundwater types in the coastal area of Ujong Pancu, Peukan Bada, Aceh Besar are characterized by three main hydrochemical facies: Ca–Mg–HCO_3, mixed facies, and Na–HCO_3–SO_4. The Ca–Mg–HCO_3 facies generally represents groundwater influenced by the recharge zone, where the chemical composition is dominated by calcium, magnesium, and bicarbonate ions derived from the initial interaction between groundwater and minerals composing the aquifer rocks (Subba Rao et al., 2024). The transition toward mixed facies indicates that groundwater has undergone hydrogeochemical evolution through more intensive water–rock interaction during groundwater flow within the aquifer system (Fosu et al., 2025). This process is characterized by increasing variation in both cation and anion compositions. Furthermore, several samples tend to evolve toward the Na–HCO_3–SO_4 facies, indicating the occurrence of cation exchange processes within the aquifer, in which Ca and Mg ions are gradually replaced by Na ions as groundwater flows farther from the recharge area.

This pattern indicates that groundwater hydrogeochemical evolution beginning from recharge-zone groundwater characterized by a Ca–Mg–HCO_3 composition. A significant increase in HCO_3 concentration reflects the dissolution of carbonate lithologies within the aquifer (Yan et al., 2024), such as reef limestone (Tlp) and coastal sand deposits (Qh) (Bennet et al., 1981). With increasing distance along the groundwater flow path, the chemical composition evolves further, marked by a shift in dominant cations from Ca–Mg to Na and the development of Na–HCO_3–SO_4 facies.

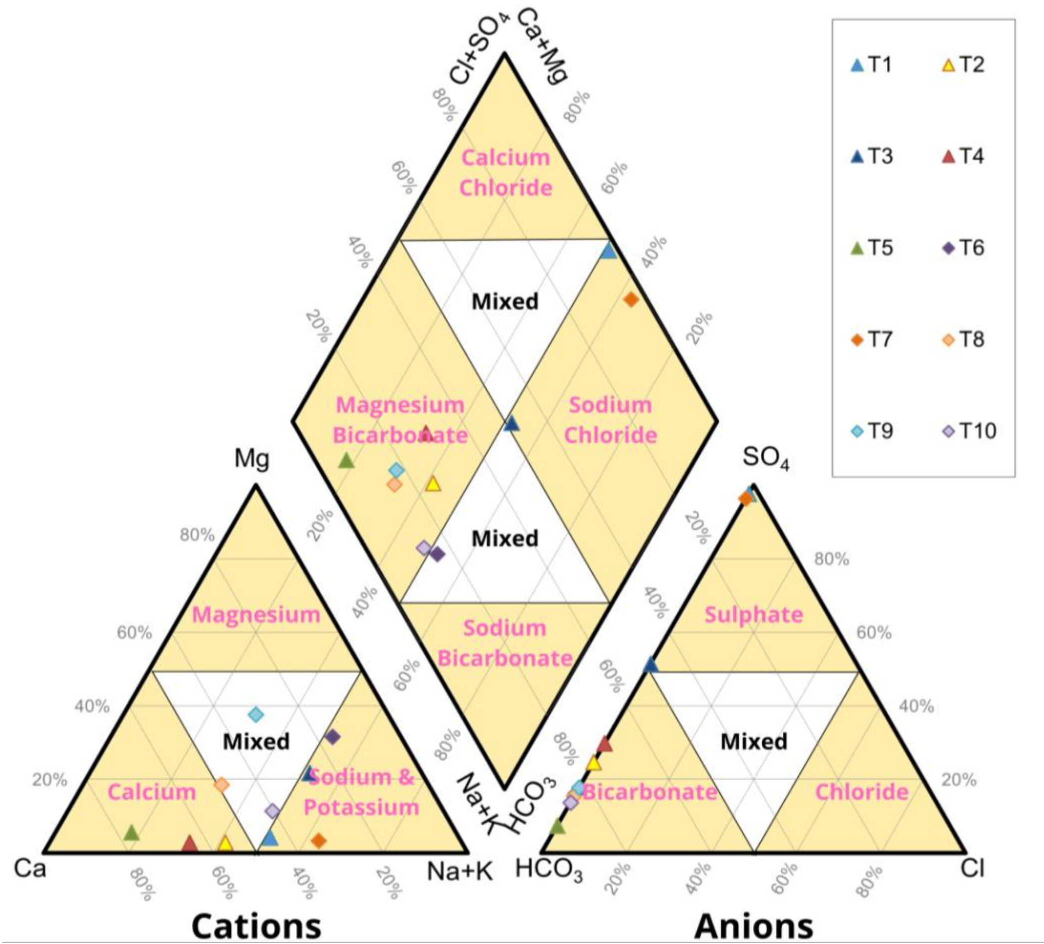

Figure 4. Piper Diagram of the Research Area

An integrated hydrogeochemical interpretation was conducted by combining the Piper diagram and Stiff diagram analyses to obtain a more comprehensive understanding of groundwater characteristics and evolution. Based on the Piper diagram plotting, groundwater in the coastal area of Ujong Pancu, Peukan Bada, Aceh Besar is characterized by three main hydrochemical facies: Ca–Mg–HCO_3, mixed facies, and Na–HCO_3–SO_4. The Ca–Mg–HCO_3 facies generally represents relatively young groundwater originating from the recharge zone, while the mixed facies reflect a transitional stage of hydrochemical evolution. Further development toward the Na–HCO_3–SO_4 facies indicates the occurrence of cation exchange processes along the groundwater flow path.

These findings are consistent with the interpretation derived from the Stiff diagram, which shows several dominant groundwater types, including Ca–HCO_3, Na+K–HCO_3, and Na+K–SO_4. The Ca–HCO_3 type represents groundwater in the early stage of hydrogeochemical evolution and is still influenced by meteoric water from the recharge zone. In contrast, the Na+K–HCO_3 and Na+K–SO_4 types indicate the progressive evolution of groundwater chemistry due to water–rock interaction and ion exchange processes within the aquifer system. The agreement between the Piper and Stiff diagram interpretations suggests that the hydrogeochemical evolution of groundwater in the study area is primarily controlled by carbonate mineral dissolution, water–rock interaction, and cation exchange during groundwater flow (Muhni et al., 2025).

These conditions are closely related to the geological characteristics of the study area, which is dominated by alluvial deposits composed of unconsolidated materials such as sand, silt, gravel, and clay (Sartika et al., 2025). Alluvial deposits generally exhibit relatively high porosity and permeability, allowing intensive groundwater circulation and enhancing water–rock interaction processes (Morici et al., 2023). These processes can increase carbonate mineral dissolution and ion exchange reactions (Liu et al., 2025), which subsequently influence the evolution of groundwater chemical composition (Qin et al., 2025). Therefore, the hydrogeochemical characteristics of groundwater in the Ujong Pancu coastal area are controlled not only by groundwater flow processes but also by the hydrogeological properties of the alluvial deposits that form the local aquifer system (Khan et al., 2025).

CONCLUSIONS

Based on an integrated analysis using Piper and Stiff diagrams, the hydrogeochemical characteristics of groundwater in the Ujong Pancu coastal area are classified into three main facies: Ca–Mg–HCO_3, mixed facies, and Na–HCO_3–SO_4. This pattern reflects the progressive stages of groundwater hydrogeochemical evolution, transitioning from initial recharge conditions to more evolved states along the groundwater flow path. The Ca–Mg–HCO_3 facies and Ca–HCO_3 type indicate relatively young groundwater influenced by meteoric water, whereas the evolution toward Na–HCO_3–SO_4 facies and Na+K–HCO_3 and Na+K–SO_4 types suggests the dominance of cation exchange and water–rock interaction processes. The elevated HCO_3^- concentrations further suggest significant carbonate dissolution associated with aquifer lithology composed of Reef Limestone (Tlp) and Coastal Sand Deposits (Qh). Several samples still exhibit Ca–Mg–HCO_3 facies with relatively balanced ionic compositions, representing recently recharged meteoric groundwater with limited hydrochemical evolution (Mei et al., 2024). Overall, the groundwater chemistry is primarily controlled by ion exchange mechanisms and carbonate rock dissolution within the aquifer system.

However, several limitations should be acknowledged. The relatively limited number of samples and spatial coverage may constrain the representativeness of the hydrogeochemical conditions across the study area (Luo et al., 2017). In addition, the analytical scope, which focuses primarily on major ions, may not fully capture more complex processes involving trace elements or isotopic signatures. Future research should therefore incorporate higher-resolution spatial sampling, temporal monitoring, and advanced geochemical approaches such as isotope tracers and reactive transport modeling to provide a more comprehensive understanding of groundwater evolution and its controlling mechanisms in coastal aquifer systems.

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